

THIN FILM CELL DEVELOPMENT WORKSHOP REPORT

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INTRODUCTION

The workshop was co-chaired by Vijay K. Kapur and James R. Woodyard, and attended by a number of people, some of whom drifted in and out during the two hour session. Sixteen people signed the attendance sheet which was circulated during the workshop. Seven questions were presented for discussion to the workshop co-chairs prior to the workshop by the SPRAT XI Conference organizers. The questions are enumerated below as Q1 through Q7. The questions were reviewed by the workshop attendees at the beginning of the workshop and an additional three questions were added; these are listed below as Q8-Q9.

As the workshop progressed, it became apparent that attendees had different views on the reasons thin-film cells are attractive for space applications. Towards the end of the workshop, the author took the liberty of posing a survey question in an effort to give attendees the opportunity to express their views on the topics discussed during the workshop. Eleven attendees submitted written responses to the questionnaire. Considering that responding to the survey question was at the expense of attending the happy hour, eleven responses is considered respectable. The responses were summarized by the author and are tabulated below in the section: SURVEY QUESTION.

The issue of using thin-film cells in orbits ranging from LEO to GEO was debated during the workshop and in the halls following the workshop, and during the workshop summary presentation. The author has taken the liberty to present another point of view on this matter considering AP8MIN and AE8MAX calculations; these comments are presented below in the section entitled: RADIATION AND EARTH ORBITS.

Three written communications were received following the workshop. The communications have been included in the development of the report.

The author assumes full responsibility for the contents of the workshop report.

Q1: WHAT ARE POTENTIAL THIN-FILM CELLS?

Cells made from CdTe, CIS and a-Si alloys were stated as potential thin-film cells. Each of the mentioned cell types involve a technology which is implied in stating the material.

Q2: WHAT UNIQUE PERFORMANCE CAPABILITIES DO THIN-FILM CELLS OFFER?

Thin-film cells offer the potential for high specific power density, low cost, flexible arrays, monolithic structures and high EOL.

Specific power densities in excess of 200 W/kg have already been achieved; two papers presented at the conference projected specific power densities in the 500-700 W/kg range. There are applications where high specific power is necessary in order to carry out missions.

Low cost is expected because monolithic structures offer the potential for using automated fabrication technologies; there is also the potential of employing the technology developed for terrestrial applications of thin-film cells.

Flexible arrays have already been demonstrated; the capability makes it possible to use thin-film cell-based arrays for auxiliary space power applications. Flexible arrays may be transported in a canister and deployed upon demand.

Monolithic structures, in addition to offering the potential for low cost, may reduce interconnect problems. It was felt that the integrated nature of monolithic structures offer the potential for including the interconnects in the structure during the device fabrication; the problem of failure of interconnects during temperature cycling should be reduced.

High EOL, relative to thick crystalline cells, is possible because of the higher demonstrated radiation resistance of thin-film cells. Both CIS and a-Si alloys have demonstrated radiation resistances at least 50 times better than crystalline silicon. Thin-film cells may be used without coverglasses which requires an understanding of defect production by particles with energies as low as about 50 keV.

Q3: WHAT ARE THE KEY R&D ISSUES?

The key R&D issues are efficiency, stability and thermal cycling, and the effects of plasma discharges.

Efficiencies of research thin-film cells have been reported which are in excess of 10%. Manufactured large area cells have efficiencies which lag the research cells; research must be done to close the gap. Research is currently funded for terrestrial applications of thin-film cells; it is directed at improving cell efficiencies. The technology developed for terrestrial applications of thin-film cells will result in cells more attractive for space applications.

Stability of cell efficiency is necessary in order for engineers to design arrays for space applications. The effect of the environment and AMO illumination on cell efficiency must be understood. While the optical-induced instability of a-Si alloy cells (Staebler-Wronski effect) is well known, the effect of temperature cycling and AMO illumination on thin-film arrays in a space environment need to be investigated. Mention was also made that we should not overlook the effect of the harsh high-humidity environment of pre-launch.

Thermal cycling of arrays with monolithic structures is a new research area. Concern was expressed that we need to develop experience with monolithic structures to determine their stability in a space environment.

The effect of plasma discharges on thin-film cells needs to be investigated. Blanket arrays are susceptible to discharges on both sides. The role of encapsulants in protecting the blankets needs to be investigated.

Q4: WHAT ARE THE MANUFACTURABILITY ISSUES?

The manufacturability issues are size, integration, cost, flexibility and yield. These issues are common to terrestrial applications; there are a number of both private and public programs addressing these issues. While the details of arrays designed for space applications are different, both the terrestrial and space applications share manufacturability issues. It is clear that the cell engineers must look to the manufacturing engineers to delineate manufacturing problems, and to consider the problems in selecting materials and fabrication technologies for cells.

Q5: CAN THIN-FILM CELLS FOR SPACE APPLICATIONS BE LOW COST?

Yes, if the space technology feeds off the terrestrial programs. Manufacturers of thin-film cell arrays are meeting terrestrial photovoltaic needs. The thin-film photovoltaic technology has developed to the point it is because of the technological developments accomplished by the terrestrial programs. If these programs continue to develop the technology, the thin-film cell will be well positioned to meet cost and efficiency requirements for a space mission that would not be possible otherwise. The attendees speculated on cost verses volume for thin-film cells. Three projections were presented. The first cost projection was based on delivering 200 W arrays; a cost range of 500 \$/W for one array to 100 \$/W for a quantity of more than 1000 arrays. The second projection was 200 \$/W for a 5-10 kW market and 15 \$/W for a 5-10 MW market. The third estimate was given for a specific space application requiring 6450 W; the cost was estimated to be 1/5 the cost of crystalline silicon.

Q6: WHAT IS (AND IS NOT) KNOWN ABOUT RADIATION DAMAGE IN THIN-FILM CELLS? WHAT IS EXPECTED?

Research literature contains encouraging radiation resistance results. The workshop attendees view these results as preliminary and indicated that more work needs to be done. Research shows radiation resistances for thin-film cells at least 100 times better than crystalline silicon. However, the defect generation mechanisms are not well understood and should be the subject of future research. Research must consider particle energies down to about 50 keV because of the interest in using thin-film cells without

coverglasses in applications ranging from LEO to deep space. Results have been reported with particle energies in the 0.20 to 2.00 MeV range.

Q7: ARE THIN-FILM CELLS USEFUL IF THEY ARE NOT ON FLEXIBLE LIGHT-WEIGHT SUBSTRATES?

Yes, if the application involves a high radiation environment. It was felt that the documented high radiation resistance of thin-film cells makes them attractive for missions with high radiation environments. The monolithic structure of thin-film cells poses some possible advantages over thick crystalline cells, namely, stable interconnects and lower costs; these advantages could make thin-film cells attractive even if they are not on light-weight substrates.

Q8: HAVE THIN-FILM CELLS BEEN FLOWN, AND IF SO, WHAT ARE THE RESULTS?

CIS and a-Si alloy thin-film cells are in orbit on the LIPS-III satellite which was launched in the spring of 1987 into a 1100 km orbit with a 60° inclination. Raw data were transmitted to the providers of the cells during the SPRAT XI Conference by J. Severns, coordinator of the experiments.

The CIS cells were provided by Boeing Aerospace and Electronics. It was reported that the cells functioned with "no noticeable" degradation until an open-circuit condition developed after two and one-half years in space.

a-Si alloy cells were provided by Solarex and Sovonics. The Solarex cells are single-junction cells with a 300 micron coverglass and continue to function after four years in space. The outputs of the cells have degraded somewhat; it is speculated that the degradation is due to the Staebler-Wronski effect. The Sovonics cells have an ethylene vinyl acetate (EVA) encapsulant. It was reported that the degradation in the outputs of the cells suggests the EVA has deteriorated.

The workshop attendees strongly recommend that the results of the LIPS-III thin-film cell experiments be published as soon as possible. In the event that analysis of the data prior to publication is not possible, the data should be published in raw form; the details of the structures of the various cells and the space environment should also be published. At the very least, the data should be made available to parties with space applications for thin-film cells.

Q9: WHAT IS THE BEST WAY FOR THIN-FILM CELLS TO BE SPACE QUALIFIED?

The attendees were not able to come up with a procedure to space qualify thin-film cells. It was pointed out that materials have been used in thin-film cells without regard to the body of

information on materials approved for space. It would make sense for engineers to have access to resources listing materials approved for space. The terrestrial use of thin-film cells is driving the development of the technology; it appears that engineers interested in space applications do not have easy access to approved materials lists. Workshop attendees indicated that NASA sites have approved space materials lists and a Solar Cell Array Handbook has also been published which deals with space materials issues.

The issue of using space flight as a way of space qualifying cells was discussed. Those interested in this route were encouraged to contact program officers, but to be aware that they balance risk against program success in rather conservative surroundings.

SURVEY QUESTION

The workshop attendees were requested to respond to the following question in two or three sentences: Do you think thin-film photovoltaic devices will be useful for space applications. The responses were reviewed with an eye towards the reasons given to justify the response. Eleven written responses were received; all respondents indicated that they believed that thin-film photovoltaic devices will be useful for space applications. The number of respondents for each reason is listed in table 1. Note that most respondents gave more than one reason to justify a response.

Table 1. Number of Respondees Citing a Reason for an Affirmative Response to the Questionnaire.

NUMBER	REASON FOR AN AFFIRMATIVE RESPONSE
10	Good Radiation Resistance
7	Low Cost
6	Monolithic Structure
4	Flexible Substrate
2	Light Weight
1	If R&D Is Carried Out
1	If Manufacturing Technology Is Developed
1	High Specific Power
1	Auxiliary Power Unit For A Concentrator Power Unit

RADIATION AND EARTH ORBITS.

It became clear during the SPRAT XI Conference that the radiation resistance of thin-film cells makes them attractive for space applications. Indeed, the survey question shows this is the case. However, it was not clear that the dependence of the radiation environment on altitude was known. The author requested Mark Kruer, TRW Space & Technology Group, to provide some typical

integrated fluences for protons and electrons as a function of altitude. The energies covered 0.10 to 200 MeV for protons, and 0.05 to 10 MeV for electrons. The AP8MIN model was used for protons and the AE8MAX model for electrons. The AP8MIN model results are questionable below 0.60 MeV. The results do not consider the direct radiation from solar flares. The results are show in table 2; appreciation is expressed to Mark Krueer and his group at TRW for providing the calculations.

Table 2. Ten Year Integrated Fluxes At Various Altitudes

Height (km)	Inclination (degrees)	Integrated Flux	
		Proton (cm ⁻²)	Electrons (cm ⁻²)
200	28.5	1.2E11	4.3E8
200	90	8.8E9	7.4E12
1,000	30	3.8E11	5.7E14
35,790		2.8E15	1.7E16

Table 2 shows that while the integrated fluxes at 200 km for a ten-year period are less than 1E13 cm⁻² for the two inclinations considered, the radiation in LEO must be considered in the design of an array. The effect of solar flares and man-made radiation must also be considered. The differential flux is, in general, higher at lower energies. If the thin-film cells are flown without coverglasses, the effect of the lower energy particles on the stability of the cells must be understood.

Since the efficiencies of thin-film cells are lower than crystalline cells, arrays made using thin-film cells will have a larger area and increased atmospheric drag. While atmospheric drag is a problem in LEO, there are LEO applications where the use of highly radiation resistant, light-weight and low-cost arrays made from thin-film cells are attractive. It remains for the thin-film cell technology to develop to the level where the cells meet the array designer's requirements.

CONCLUSION

The Thin-Film Development Workshop provided an opportunity for those interested in the space applications of thin-film cells to debate several topics. The meeting time of the workshop was not adequate to pursue all the topics of interests to the attendees. The unique characteristics of thin-film cells and a number of issues were covered during the discussions. It is clear that there is a great deal of interest in thin-film cells; both manufacturers and space engineers have programs underway to produce arrays for space testing. Workshop attendees see space qualification as a problem; advice on the resources available and procedures to achieve space qualification are needed. It would be highly desirable for the results of the LIPS-III experiment on thin-film cells to be made available.

III-V CELL DEVELOPMENT WORKSHOP

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Naval Research Labs
Washington, DC

and

R.P. Gale
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Tauton, Massachusetts

- DEVELOPING A GOAL FOR MEANINGFUL DISCUSSION
 - WHY CONSIDER III-V CELLS AT ALL ?
 - WHAT IS THE EXISTING SPACE MISSION NEED FOR III-V CELLS ?
 - WHY SO MANY R&D APPROACHES TO III-V'S ?
- SYSTEMS PEOPLE STATED THERE ARE PROGRAMS NEEDING INCREASED EOL SPECIFIC POWER (W/kg) NOT NOW COMPATIBLE WITH Si CELLS
- COMMERCIAL COMSTAT EOL POWER REQUIREMENTS ARE ALSO PUSHING THE ENVELOPE OF EXISTING SOLAR ARRAY CAPABILITY
- DOE MANAGEMENT PHILOSOPHY REWARDS HIGHEST EFFICIENCY NUMBERS FOR SOLAR CELLS
 - PRACTICAL APPLICATION IS SECONDARY (MARKETABILITY, MANUFACTURABILITY)
- DOD CONTRACTS OFTEN DEFINE CELL EFFICIENCY PERFORMANCE FOLLOWING SPECIFIC RADIATION AND THREAT LEVELS

PRACTICAL TALK

HOW DOES A SPECIFIC III-V TECHNOLOGY ARRIVE AT
PLATEAU OF PRODUCTION OR A MAN TECH PROGRAM ?

- NOT AN EASY OR QUICK PATH - GaAs/Ge MAY HAVE TAKEN 20 YEARS FROM EARLY EFFORTS
- A NEW CELL MUST GUARANTEE SIGNIFICANT IMPROVEMENT TO MEET PERCEIVED MISSION REQUIREMENTS
 - PROBABLY WOULD HAVE AN EOL EFFICIENCY GREATER THAN GaAs/Ge OF (a. 25%, b. 50%, or c. all of the above) TO BECOME INTERESTING ENOUGH TO SPEND \$5M +.
- HOW DO YOU JUSTIFY A NEW CELL MAN TECH THRUST ?
 - WHAT DO SYSTEMS PEOPLE LOOK FOR ?

HOW SYSTEMS PEOPLE RESPOND

- GIVE ME EOL SPECIFIC POWER (W/kg) NUMBERS BECAUSE BOL EFFICIENCY IS PRACTICALLY MEANINGLESS WHEN DESIGNING ARRAY FOR A TOTAL MISSION
- GIVE ME LOW COSTS BECAUSE THIS IS A MAIN DRIVER FOR TECHNOLOGY SELECTION
 - STATED BY SDIO, JPL, AND SSD
 - I KNOW IT WILL COST MORE THAN Si SO THE EOL PERFORMANCE HAS TO BE WORTH IT!
- GIVE ME RELIABILITY ON ORBIT EQUAL TO OR BETTER THAN Si

- SPECIAL MISSION REQUIREMENTS

- WILL THIS CELL BE SURVIVABLE TO PARTICULAR THREATS
- TRADE OFFS TO CONSIDER A MORE COSTLY CELL WHICH WILL REDUCE ARRAY SIZE, THEREBY SAVING ONBOARD FUEL WEIGHT
- TOTAL POWER SYSTEM WEIGHT IS ~1/3 SPACECRAFT WEIGHT A POUND SAVED ON ARRAY GIVES MORE PAYLOAD, ETC.
- ELECTROPROPULSION SYSTEM REQUIREMENT: 60 - 90 kW AND 2×10^{16} 1 MeV E/cm² FLUENCE - CAN AFFORD TO PAY EXTRA

SYSTEMS PEOPLE HAD MUCH MORE TO ADD

- IF THE NEW CELL COST IS TOO MUCH, THE MISSION WILL SUDDENLY LOSE ITS IMPORTANCE

- WILL BE CANCELED OR MODIFIED

- **THE REAL WORLD**

- PROGRAM OFFICES ARE VERY OPEN TO NEW TECHNOLOGY ...
- BUT ... POWER SYSTEMS ARE OF LOWER PRIORITY THAN PAYLOAD OR ATTITUDE CONTROL, FOR EXAMPLE
- BUT ... IF THE NEW POWER SYSTEM IS A **BIG** WEIGHT SAVER IT CAN GET ATTENTION
- THE PROGRAM OFFICE HAS AN INPUT FOR WHO GETS THE MAN TECH PROGRAM, WHICH FOLLOWS PROGRESSIVE DEVELOPMENT AND CONFIRMATION OF CELL PERFORMANCE THROUGH FLIGHT DEMONSTRATIONS
- A REAL TURNOFF FOR PROGRAM OFFICE IS THE HIGH UPFRONT COST OF CELL R&D AND EARLY PRODUCTION COSTS

LIFE CYCLE COSTS

- LIFE CYCLE COSTS FOR THE OVERALL SPACE MISSION CAN VINDICATE A HIGHER CELL COST IN CERTAIN CASES

- A POST WORKSHOP COMMENT TO THE CHAIRMEN -

LIFE CYCLE COST ANALYSIS IS STARTING INDUSTRY IN EARLY R&D STAGES TO ELIMINATE LESS FAVORABLE PROJECTS AND FUND A FEW GOOD ONES AT HIGHER LEVELS

- WHO WOULD IMPLEMENT SUCH A PLAN IN III-V's ?

SUMMARY OF HOW MAN TECH PROGRAM GETS ACCEPTED

1. THE CELL MUST HAVE HIGH MARKS IN A SYSTEM ANALYSIS
2. CELL DEVELOPMENT WILL BE DONE AT R&D LEVEL, AND NOT PRESCRIBED BY SYSTEM REQUIREMENTS, USUALLY
3. CELL MUST HAVE PASSED SPACE QUALIFICATION, FLIGHT DEMONSTRATIONS, RELIABILITY, GOOD END OF LIFE EFFICIENCY, AND PROBABLY LOOK LIKE A TWO-TERMINAL DEVICE
4. ADVANCED DEVELOPMENT PHASE IS UNDERTAKEN, SHOWING A COST ADVANTAGE TO SPECIFIC MISSION PLANNERS AND BE AS RISK FREE AS PRESENTLY USED CELLS
5. COMMERCIAL MANUFACTURING COSTS MUST BE CONSIDERED IN COSTING OUT THE NEW DEVICE

SOME SPECIFIC THOUGHTS ON NEW TECHNOLOGIES

- NEED A NATIONAL OR WORLD WIDE SUPPORTING MATERIAL CAPABILITY FOR NEW MATERIALS, SUCH AS IN ?
- GaAs CELL COSTS WERE VERY HIGH UNTIL THE HETEROEPITAXIAL GaAs/Ge WAS DEVELOPED
- 400,000 2 X 4 cm GaAs/Ge HAVE BEEN PRODUCED IN FLIGHT PROGRAMS CAPABILITY FOR NEW MATERIALS, SUCH AS IN ?
 - COST IS GENERALLY TOO HIGH FOR MOST MISSIONS
- InP - LATTICE CELLS WILL HAVE TO BE GROWN ON Si TO RECEIVE SERIOUS ATTENTION, ULTIMATELY

CONCENTRATOR ARRAYS

- CONCENTRATOR ARRAYS MAKE SOME SYSTEM PLANNERS NERVOUS
 - SPACECRAFT HAVE BEEN KNOWN TO SUDDENLY LOSE ATTITUDE CONTROL
 - GROUND COMMANDS OVER MANY HOURS ARE NEEDED TO RESTORE
 - THE BATTERIES COULD COMPLETELY DISCHARGE IF ONLY CONCENTRATOR PV WAS ONBOARD
- SDIO SUPER POWER SYSTEM HAS AUTONOMOUS CONTROL
 - WILL CORRECT QUICKLY ATTITUDE CONTROL FAILURE
 - THIS DEGREE OF AUTONOMY MAY NOT BE APPROPRIATE FOR SMALLER POWER MISSIONS
- CONCENTRATOR ARRAY HAS MORE EOL SPECIFIC POWER THAN APSA

SUMMARY

WE HAD A VERY GOOD EXCHANGE OF INFORMATION AND IDEAS. THE COMMENTS FROM SYSTEM-TYPE PEOPLE WERE ESPECIALLY ENLIGHTENING TO SOME R&D PEOPLE, WHO MAY HAVE GOTTEN NEW INSIGHT INTO THE REAL WORLD OF PV USERS.

ALTHOUGH WE DIDN'T DISCUSS THE MERITS OF SPECIFIC III-V TECHNOLOGIES, WE GOT AN APPRECIATION FOR THE DIVERSE CONTRIBUTIONS AND PERSPECTIVES OF THOSE WHO CONSTITUTE THE PV SPECIALIST COMMUNITY.